





1 of viewer 105 to be moved. For example, an immersive video  
2 can be made to capture a flight in the Grand Canyon. The  
3 user of an immersive video display system would be able to  
4 take the flight and look out at the Grand Canyon at any  
5 angle. Camera systems for environment mappings can be  
6 easily converted for use with immersive videos by using  
7 video cameras in place of still image cameras.

8 Many conventional camera systems exist to capture the  
9 entire environment of viewer 105. For example, cameras can  
10 be adapted to use hemispherical lens to capture a hemisphere  
11 of sphere 110, i.e. half of the environment of viewer 105.  
12 By using two camera with hemispherical lens the entire  
13 environment of viewer 105 can be captured. However, the  
14 images captured by a camera with a hemispherical lens  
15 require intensive processing to remove the distortions  
16 caused by the hemispherical lens. Furthermore, two cameras  
17 provides very limited resolution for capturing the  
18 environment of viewer 105. Thus, environment mapping using  
19 images captured with cameras using hemispherical lenses can  
20 only produce low resolution displays while still requiring  
21 intensive processing.

22 Other camera systems use multiple outward facing  
23 cameras based on the five regular polyhedrons, also known as  
24 the platonic solids. Specifically, each cameras of the  
25 camera system point radially outward from a common point,  
26 e.g. the origin of the three dimensional space, towards the  
27 center of a face of the regular polyhedron. For example, as  
28 illustrated in Fig. 2, conceptually, a cube 220 (also called  
29 a hexahedron) surrounds sphere 110. As illustrated in Fig.  
30 2(b) camera system 250 includes cameras 251, 252, 253, 254,  
31 255, and 256. Camera 256, which is obstructed by camera 251  
32 is not shown. Fig 2(b) is drawn from the perspective of

1 looking down on the camera system from the Z axis with the  
2 positive Z axis coming out of the page. Each cameras faces  
3 outward from the origin and point towards the center of a  
4 face of the cube. Thus, cameras 251 and 256 are on the Z-  
5 axis and face out of the page and into the page,  
6 respectively. Similarly, cameras 252 and 254 are on the Y  
7 axis and points up and down on the page respectively.  
8 Cameras 253 and 255 are on the X axis and point to the right  
9 and to the left of the page, respectively. Similar  
10 approaches can be used for each of the 4 other regular  
11 polyhedrons (i.e., tetrahedrons, octahedrons, dodecahedrons,  
12 and icosahedrons).

13 However, camera systems based on regular polyhedrons  
14 have poor utilization of the image data provided by standard  
15 cameras. Specifically, as illustrated in Fig. 3(a),  
16 standard cameras provide a rectangular image 310 having a  
17 long side 315 and a short side 317. The ratio of width to  
18 the height of an image is defined as an aspect ration.  
19 Thus, the length of long side 315 and short side 317 is  
20 called the aspect ratio of rectangular image 310. Typical  
21 aspect ratios include 4:3 (1.33) and 16:9 (1.78). Regular  
22 polyhedron have faces formed by triangles, squares, or  
23 pentagons. The short side of rectangular image 310 must  
24 encompass the face of the polyhedron. Therefore, as shown  
25 in Figs. 3(b)-3(d) most of the image data captured by  
26 conventional cameras are not used by an environment capture  
27 system. Specifically, Fig 3(b) shows a square face 320 of a  
28 hexahedron within rectangular image 320. Similarly, Fig.  
29 3(c) shows a triangular face of a tetrahedron, octahedron,  
30 or icosahedron within rectangular image 310 and Fig. 3(d)  
31 shows a pentagonal face of an dodecahedron within  
32 rectangular image 310. Typically, the short side of

1 rectangular image 310 is slightly larger than the polyhedral  
 2 face to allow some overlap between the various cameras of  
 3 the camera system. The overlap allows for minor alignment  
 4 problems which may exist in the camera system. An  
 5 environment capture system would only use the data within  
 6 the faces of the polyhedron while the rest of rectangular  
 7 image 310 is not used. Thus, only a small portion of the  
 8 image data captured by each camera is utilized to generate  
 9 the environment map. Consequently, even the use of multiple  
 10 cameras arranged using regular polyhedrons may not provide  
 11 enough resolution for quality environment mapping systems.  
 12 Hence, there is a need for an efficient camera system for  
 13 use with environment mapping and immersive videos.

14  
 15 SUMMARY OF THE INVENTION

16 Accordingly, the present invention provides an  
 17 efficient camera system that utilizes the asymmetry of  
 18 conventional camera to efficiently capture environments. In  
 19 one embodiment of the present invention, an outward facing  
 20 camera system includes a plurality of equatorial cameras.  
 21 The equatorial cameras face radially outward from an origin  
 22 and are located in or near a plane. Generally, the  
 23 equatorial cameras are distributed evenly about the origin  
 24 so that each equatorial camera is offset from an adjacent  
 25 camera by the same equatorial adjacent angle. The outward  
 26 facing camera system also includes a plurality of polar  
 27 cameras tilted above the plane. Generally, the polar  
 28 cameras also face radially outward from the origin and are  
 29 all tilted by the same equatorial offset angle. However,  
 30 some embodiments may include polar cameras having different  
 31 equatorial offset angles.

1       The equatorial offset angle is chosen to insure  
 2 complete camera coverage of an environment. Therefore, the  
 3 equatorial offset angle is chosen to eliminate gaps between  
 4 the fields of view of the polar cameras and the equatorial  
 5 cameras. Thus, the equatorial offset angle is generally  
 6 selected to cause some overlap between the field of view of  
 7 the polar cameras and the equatorial cameras. The outward  
 8 facing camera system can also include one or more polar  
 9 cameras tilted below the plane. The present invention will  
 10 be more fully understood in view of the following  
 11 description and drawings.

12  
 13 BRIEF DESCRIPTION OF THE DRAWINGS

14       Fig. 1 is a three-dimensional representation of a user  
 15 and an environment.

16       Fig. 2(a) is a three-dimensional representation of an  
 17 environment surrounded by a cube.

18       Fig. 2(b) is a three-dimensional diagram of a  
 19 conventional camera system based on a cube.

20       Fig. 3(a)-3(d) illustrates inefficiencies of polyhedron  
 21 faces and rectangular image capture.

22       Fig. 4 is a three-dimensional diagram of part of an  
 23 asymmetrical camera system in accordance with one embodiment  
 24 of the present invention.

25       Fig. 5(a) is a three-dimensional diagram of an  
 26 asymmetrical camera system in accordance with one embodiment  
 27 of the present invention.

28       Fig. 5(b) is a diagram of part of an asymmetrical  
 29 camera system illustrating overlapping fields of view.

30       Fig. 5(c) is a conceptual diagram illustrating fields  
 31 of view for a cameras system an accordance with one  
 32 embodiment of the invention.

1        Fig. 5(d) is a conceptual diagram illustrating fields  
2 of view for a cameras system an accordance with one  
3 embodiment of the invention.

4        Fig. 6(a)-6(c) are conceptual diagrams of fields of  
5 view to illustrate some benefits of rotated fields of view.

6        Fig. 7 is a three-dimensional diagram of an  
7 asymmetrical camera system in accordance with one embodiment  
8 of the present invention.

9  
10    DETAILED DESCRIPTION

11        As explained above, camera systems for environment  
12 mapping should have a spherical field of view to capture the  
13 entire environment around a viewer. Symmetrical camera  
14 systems based on regular polyhedrons are inefficient because  
15 conventional cameras typically produce rectangular images.  
16 Thus, much of the image data captured by the cameras of  
17 symmetrical camera systems are not used by the environment  
18 mapping system.

19        In accordance with the present invention, asymmetrical  
20 camera systems are adapted to utilize a greater proportion  
21 of the image data from each camera as compared to  
22 symmetrical camera systems, which are based on regular  
23 polyhedrons. Figs. 4, 5(a), and 6 show various parts of a  
24 camera system 400 in accordance with one embodiment of the  
25 present invention. Camera system 400 includes a plurality  
26 of equatorial cameras 410, 420, 430, and 440. In camera  
27 system 400, four equatorial cameras are used. However,  
28 other embodiment of the present invention may use a  
29 different number of equatorial cameras. As used herein,  
30 equatorial cameras refer to a set of cameras in or near an  
31 equator of sphere 110. For convenience and clarity,

1 equatorial cameras are described as being in or near the XY  
2 plane.

3       The plurality of equatorial cameras face radially  
4 outward from the origin and should be distributed evenly  
5 about the origin. Each equatorial camera is offset from an  
6 adjacent camera by an equatorial adjacent angle. For  
7 example, as shown in Fig. 4, camera 410 and camera 420 are  
8 offset by equatorial adjacent angle 415. As used herein, a  
9 first camera is adjacent to a second camera, if the field of  
10 view of the first camera overlaps the field of view of the  
11 second camera. Generally, the equatorial adjacent angle  
12 should equal 360 degrees divided by the number of equatorial  
13 cameras. Thus, when the plurality of equatorial cameras  
14 includes 4 cameras, the equatorial adjacent angle is 90  
15 degrees. For clarity, equatorial cameras 410, 420, 430, and  
16 440 are shown to be on the X and Y axes of Fig. 4.  
17 Specifically, camera 410 is located on the positive Y axis  
18 pointing in the positive Y direction, camera 420 is on the  
19 positive X axis pointing in the positive X direction, camera  
20 430 is on the negative Y axis pointing in the negative Y  
21 direction, and equatorial camera 440 is on the negative X  
22 axis pointing in the negative X direction.

23       The number of equatorial cameras in a camera system is  
24 dictated by the field of view of the cameras used in the  
25 camera system. A camera C has a rectangular field of view,  
26 for convenience the dimension of the field of view are  
27 called a horizontal field of view  $C_H$  and a vertical field  
28 of view  $C_V$ . The full rectangular field of view is labeled  
29 with reference name  $C_F$ . Horizontal field of view  $C_H$  is  
30 defined with respect to the XY plane. Vertical field of  
31 view is defined with respect to ZX plane or the ZY plane.  
32 In general, the horizontal field of view of each equatorial





1 The practical maximum and minimum limit of an  
2 equatorial offset angle 514 is determined with reference to  
3 Fig 5(b) for camera systems in which the field of view of  
4 the polar cameras and equatorial cameras are aligned with  
5 the XY plane. Furthermore, the following explanations are  
6 made based on rectangular projections of the field of view  
7 of the various equatorial and polar cameras. In actual use,  
8 the rectangular projections do not produce rectangular  
9 fields of view on sphere 110. Thus, many small inaccuracies  
10 exist in the following calculations of equatorial offset  
11 angles. However, by allowing a small but significant  
12 overlap between the fields of view, these small inaccuracies  
13 can be ignored. Actual camera projections on a sphere 110  
14 can be generated using 3-D projection system such as  
15 Powerstitch<sup>TM</sup> by Enroute Inc., ~~which is available for~~  
16 ~~purchase over the internet at "http://www.enroute.com".~~

17 Fig 5(b) is drawn from the perspective of looking down  
18 the Y axis with the negative Y axis coming out of the page.  
19 Furthermore, for clarity, only equatorial camera 440 and  
20 polar camera 510, which are offset by equatorial offset  
21 angle 514, are shown in Fig. 5(b). Equatorial camera 440  
22 has a vertical field of view 440\_V. Polar camera 510 has a  
23 vertical field of view 510\_V. To ensure complete coverage  
24 of the environment, vertical field of view 510\_V and  
25 vertical field of view 440\_V should overlap Furthermore,  
26 vertical field of view 510\_V should extend to the Z axis.

27 Since both the vertical and horizontal field of view of  
28 a camera is centered about the center of the camera, half of  
29 vertical field of view 440\_V extend above the XY plane.  
30 Similarly half of vertical field of view 510\_V extends  
31 radially from the center of polar camera 510 towards  
32 equatorial camera 440. Thus, equatorial offset angle 514





1 intersection of ray 565 with sphere 110 and parallel to the  
2 XY plane. Horizontal field of view 510\_H is marked by rays  
3 585 and 595. The radius of circle 110\_3 is smaller than the  
4 radius of circle 110\_2, which is defined to be equal to one.  
5 Specifically, the radius of circuit 110\_3 is equal to the  
6 cosine of angle 547 (Fig. 5(c)). Angle 547 is equivalent to  
7 half of vertical field of view 440\_V of equatorial camera  
8 440. Although angular field of view has been used above to  
9 determine the number of equatorial cameras, angular field of  
10 view is actually a proxy for arc length coverage. However,  
11 because sphere 110 is defined to have a radius of one, arc  
12 length and angular field of view are equivalent measures for  
13 equatorial cameras. However, for polar cameras the actual  
14 radius of the sphere for horizontal field of view is less  
15 than one. Thus, the angular horizontal field of view is not  
16 a direct proxy for arc length. Therefore, the horizontal  
17 field of view of polar cameras must be divided by the radius  
18 of sphere 110\_3, i.e. the cosine of half of vertical field  
19 of view 440\_V. Thus, for an embodiment of camera system 400  
20 using both equatorial cameras and polar cameras having a  
21 vertical field of view of approximately 76 degrees and a  
22 horizontal field of view of approximately 104 degrees, the  
23 number of polar cameras necessary for complete environment  
24 coverage is an integer greater than or equal to 360  
25 multiplied by cosine of 38 degrees divided by 104 degrees  
26 (i.e.  $360 * \cos(38)/104$  equals approximately 2.737).  
27 Therefore, in this embodiment three polar cameras are used  
28 in the first plurality of polar cameras.

As explained above, the derivation of equatorial offset angles and the estimated number of polar cameras assumed that the fields of view of the equatorial and polar cameras are aligned with the XY plane. However, some embodiments

the present invention includes cameras that are rotated along the optical axis of the camera. Rotation along the optical axis in many cases may allow complete coverage in situations where having all fields of view aligned with the XY axis may fail to provide complete coverage. Figs. 6(a)-6(c) illustrates some benefits that may be obtained from rotation of the field of view. For clarity, Figs 6(a)-6(c) use rectangular projection; however, as explained above in actual use, the rectangular projections do not produce rectangular fields of view on sphere 110. However, the inaccuracies introduced by this simplification do the greatly diminish benefits being illustrated. Specifically, in Fig. 6(a) a field of view 610\_F and a non overlapping field of view 620\_F are shown. However, as illustrated in Fig. 6(b), by rotating field of view 610\_F, field of view 610\_F can be made to overlap field of view 620\_F. Additional rotated fields of view such as field of view 640\_F can also be used for complete coverage of the environment. Fig. 6(c) shows a rotated field of view 640\_F with a field of view 650\_F. By rotating field of view 640\_F, the effective horizontal field of view for field of view 640\_F is increased. The increase of increased effective horizontal field of view is illustrated by field of view 640\_F fully encompassing the top side of field of view 650\_F. In general, the use of rotated field of views provide a mixture of benefits and additional complications. The use of rotated field of views can be greatly simplified by using a 3-D projection system such as Powerstitch™ to insure complete coverage of the environment.

30 As illustrated in Fig. 7, camera system 400 also  
31 includes a second plurality of polar cameras. Specifically,  
32 the second plurality of polar cameras includes polar cameras

1 710, 720 and 730 Fig. 7 is drawn from the perspective of  
2 looking down the X axis with the negative X axis coming out  
3 of the page. Polar cameras 710, 720, and 730 face radially  
4 outward and are tilted below the XY plane by a equatorial  
5 offset angle. The equatorial offset angle is dependent on  
6 the vertical field of view the equatorial cameras and the  
7 polar cameras. Although, camera system 400 includes three  
8 polar cameras in both the first plurality and the second  
9 plurality of polar cameras, other embodiments of the present  
10 invention may include differing numbers of polar cameras in  
11 the first plurality and the second plurality of polar  
12 cameras. Furthermore, some embodiments of the present  
13 invention may include a single polar camera below the XY  
14 plane.

15 In the above-described manner, efficient outward facing  
16 camera systems are made possible. Specifically, an outward  
17 facing camera system in accordance with embodiments of the  
18 present invention has better utilization of the image data  
19 from each of the cameras than convention camera systems.  
20 Thus, a camera system in accordance with the present  
21 invention can use a fewer number of cameras and still  
22 provide higher resolution environment maps than conventional  
23 camera systems. The various embodiments of the structures  
24 and methods of this invention that are described above are  
25 illustrative only of the principles of this invention and  
26 are not intended to limit the scope of the invention to the  
27 particular embodiments described. For example, in view of  
28 this disclosure, those skilled in the-art can define other  
29 equatorial cameras, polar cameras, equatorial offset angles,  
30 equatorial adjacent angles, equatorial tilt angles, polar  
31 adjacent angles, vertical fields of view, horizontal fields  
32 of view, and so forth, and use these alternative features to

1 create a method or system according to the principles of  
2 this invention. Thus, the invention is limited only by the  
3 following claims.